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Quantifying the Impacts of Nuclear Weapons Enterprise Consolidation

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Quantifying the Impacts of Nuclear Weapons Enterprise Consolidation

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Abstract

The United States Department of Energy nuclear weapons complex has undergone substantial consolidation in the decades since the Cold War. The extent of this consolidation is best illustrated through the inter-related impacts on the nuclear infrastructure, stockpile, and critical skills of the weapons workforce. This paper reviews impacts in each of these areas and their implications on the weapons complex as a whole. With regard to future consolidation efforts, the National Nuclear Security Administration uses a variety of mathematical tools to quantify the potential effects of future stockpile decisions. This paper discusses several examples of such tools and how they have successfully been used to aid and inform policy decisions.

Overview of Weapons Enterprise Consolidation

The control of production, design, and testing of nuclear weapons in the United States is housed within the Department of Energy (DOE). Formerly the Atomic Energy Commission, this civilian agency was intentionally established separately from the Department of Defense (DoD), which is tasked with deploying such weapons. This dichotomy helps to ensure a balance of power among the entities responsible for the country's most powerful weapons, in that their ultimate ownership lies outside the military that might be using them.

Infrastructure

Within the Department of Energy, the National Nuclear Security Administration (NNSA) manages the day-to-day operations of the country's nuclear production, design, and testing labs. At the height of the Cold War, there were sixteen such sites located around the country (Figure 1a); as of 2012, only nine sites remain within the NNSA complex (Figure 1b), a downsizing rate of more than forty percent. Of the seven sites that have left the complex, one is now a DOE lab engaged in non-weapons activities (Idaho), one is commercially managed (Pinellas), and the other five have closed and are undergoing environmental remediation and cleanup activities.

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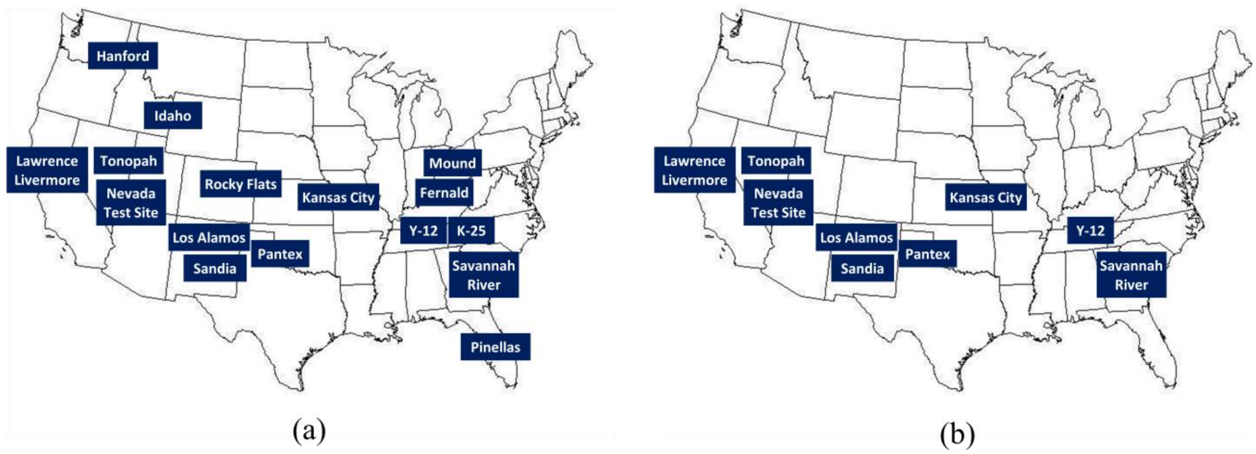

Figure 1. Department of Energy nuclear weapons complex sites in 1980 (a) and 2012 (b).

Of the existing nine sites, there are three nuclear design and engineering labs (Lawrence Livermore, Los Alamos, and Sandia), four production sites (Pantex, Kansas City, Y-12, and Savannah River), and two testing sites (Nevada Test Site and Tonopah Testing Range, which is managed by Sandia). The square footage of these sites is additionally undergoing consolidation: NNSA is currently implementing a plan to eliminate nearly a third of the current complex footprint, from 35 million to 26 million square feet.[2] Since 2002, the Y-12 plant alone has eliminated approximately 1.3 million square feet.[3]

The goal of NNSA's current infrastructure funding is to modernize and revitalize certain key facilities, while sustaining capabilities at many others, to ensure the complex retains sufficient capacity to meet its primary mission functions.[4] Deferred maintenance is a key issue in sustainment, and NNSA is currently working to eliminate $900 million of legacy deferred maintenance in its existing facilities.[5] As the total complex real property is valued at roughly $40 billion, this represents a significant portion of the whole.[6]

Stockpile

Recently declassified stockpile numbers illustrate the extent to which the US nuclear stockpile has shrunk since the height of the Cold War (Figure 2): as of September 2009 the stockpile had declined nearly 84 percent from its maximum at the end of 1967, and over 75 percent since the fall of the Berlin Wall in 1989.[7] In addition, the number of non-strategic

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[2] US Department of Energy, *Final Complex Transformation Supplemental Programmatic Environmental Impact Statement* (Washington, DC: DOE, October 2008), S-31, http://nnsa.energy.gov/aboutus/ourprograms/defenseprograms/complextransformation.

[3] US Department of Energy, *Final Site-Wide Environmental Impact Statement for the Y-12 National Security Complex* (Washington, DC: DOE, February 2011), 2-10, http://www.y12sweis.com/y12document.html.

[4] US Department of Energy, *FY 2012 Stockpile Stewardship and Management Plan* (Washington, DC: DOE, April 2011), 33.

[5] Ibid., 102.

[6] Clifford Shang and Bernard Mattimore, *Forward-Projection, Risk-Based Metrics in an Infrastructure Margins and Uncertainty (IMU) Framework* (Technical Report COPJ-2011-0630, Lawrence Livermore National Lab, 2012), 3.

[7] US Department of Defense, *Fact Sheet: Increasing Transparency in the US Nuclear Weapons Stockpile* (Washington, DC: DoD, May 2010), 1, http://www.defense.gov/news/d20100503stockpile.pdf.

weapons has fallen by approximately 90 percent in the last two decades[8]. This extraordinary consolidation is consistent with arms control limitations specified by the START and SORT treaties and reflects the evolving role of nuclear weapons in US foreign policy.

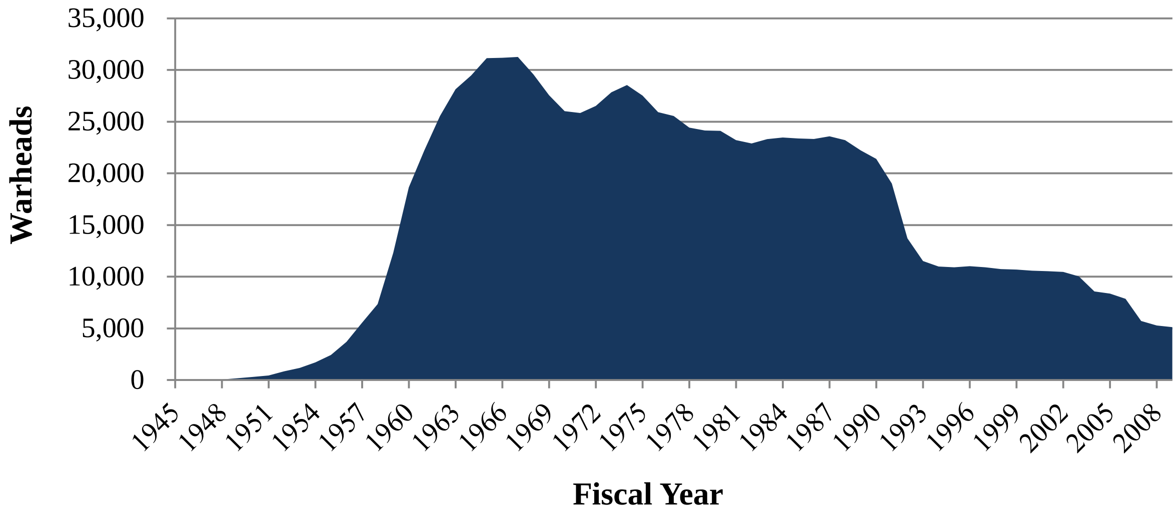

Figure 2. United States nuclear weapons stockpile (active and inactive weapons), 1945-2009.[9]

Concurrent with the decline of the stockpile itself has been a great increase in the number of nuclear weapons undergoing dismantlement: from fiscal years 1994-2009, over 8700 weapons were dismantled, with an additional several thousand awaiting dismantlement in coming years.[10] Numerous weapon systems have completed final dismantlement, including most recently the W62 ICBM (in 2010)[11] and the massive B53 bomb (in 2011)[12]. All weapons retired prior to 2009 are currently scheduled to be dismantled no later than the end of fiscal year 2022.[13]

NNSA's current stockpile goals include performing annual surveillance to ensure the safety and effectiveness of the current stockpile; initiating life extension programs (LEPs) to address aging issues in current stockpile systems; reducing the number of warhead types by pursuing options for adaptable warheads that are deployable across different platforms; and completing all scheduled dismantlements in a timely manner.[14] This supports the agency's previously stated goals to maintain the smallest possible stockpile that is consistent with national security needs.[15]

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[8] Ibid., 1.
[9] Data are from Ibid., 1; and US Department of Energy, "Declassified Stockpile Data 1945 to 1994" (press release, June 27, 1994), https://www.osti.gov/opennet/forms.jsp?formurl=document/press/pc26tab1.html.
[10] Ibid., 1.
[11] US Department of Energy, "Energy Secretary Announces Completion of W62 Dismantlement Program" (press release, August 12, 2010), http://www.nnsa.energy.gov/mediaroom/pressreleases/chupantex081210.
[12] US Department of Energy, "NNSA Announces Dismantlement of Last B53 Nuclear Bomb" (press release, October 25, 2011), http://nnsa.energy.gov/mediaroom/pressreleases/b53dismantle102511.
[13] US Department of Energy, *FY 2012 Stockpile Stewardship and Management Plan*, 17.
[14] Ibid., 2-3.
[15] US Department of Energy, *Final Complex Transformation SPEIS*, S-55.

Critical Skills

With the consolidation in the US nuclear weapons infrastructure and stockpile has come a corresponding decline in the size of the nuclear weapons workforce, and concerns about the retention of critical skills necessary to perform stockpile activities. The DOE weapons complex workforce has shrunk over 60 percent in the last two decades, from 51,000 employees in 1992 to 20,000 in 2007.[16] Nearly every site in the NNSA complex has experienced layoffs or voluntary separation initiatives over the past decade.

The nuclear workforce itself is considerably older than the population of the US at large (Figure 3): as of 2007, more than 40 percent of DOE laboratory essential workers and 45 percent of weapons plant workers were over the age of 50.[17] A large majority of the DOE weapons workforce will be eligible for retirement in the next ten years; this has not been offset by recent hiring trends, which suggests the workforce size will continue to decline.[18] There is a real and valid concern that the specialized skills required in maintaining the country's nuclear deterrent may be lost unless attention is devoted to their sustainment.

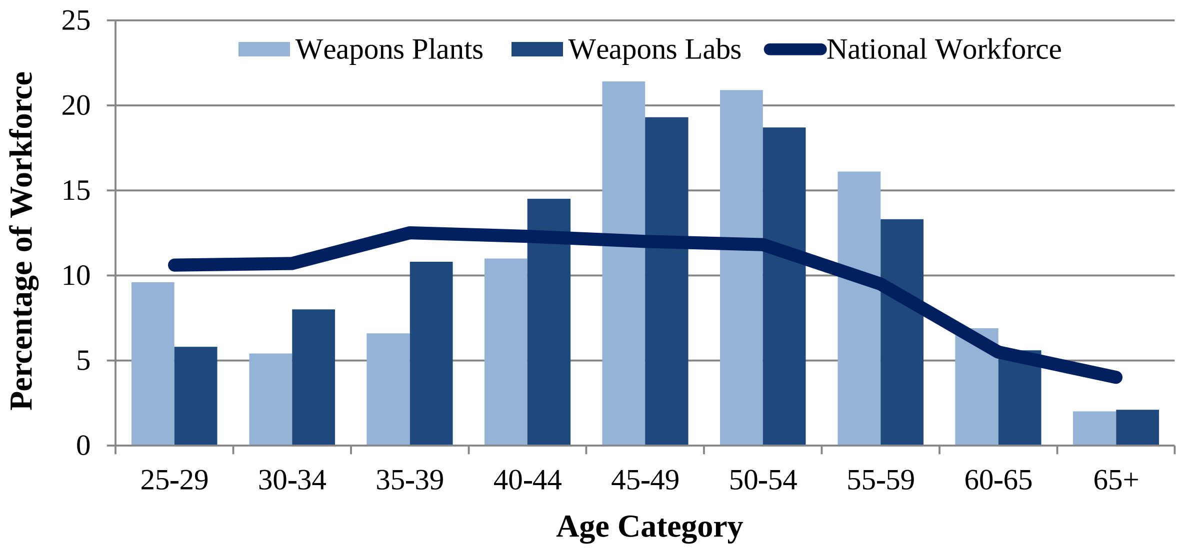

Figure 3. Demographics of DOE weapons plants and labs, compared to the national workforce.[19]

A major challenge for NNSA is ensuring that a new generation of weapons designers, code developers, experimentalists, stewards, and engineers are capable of a fundamental understanding of nuclear weapons, in an environment in which computer-aided design has taken the place of hands-on testing. Their goals for the future include introducing occasions for such critical skills to be exercised, through annual safety and security assessments and opportunities to develop and mature technologies with the potential for stockpile modernization.[20] This includes

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[16] US Department of Defense, *Report of the Defense Science Board Task force on Nuclear Deterrence Skills* (Washington, DC: DoD, September 2008), 61, http://www.acq.osd.mil/dsb/reports/ADA487983.pdf.
[17] Ibid., 61.
[18] Ibid., 60.
[19] Data are from US Department of Defense, *Report of the Defense Science Board Task force on Nuclear Deterrence Skills*, 63. For both plants and labs, the population is restricted to workers with "essential weapons program skills."
[20] US Department of Energy, *FY 2012 Stockpile Stewardship and Management Plan*, 18.

analyses of options for future lifetime extension program (LEP) activities, using a predictive capability framework capable of certifying the safety and security of weapons without testing.[21]

Interdependency

The previous data have illustrated the extent to which the current DOE weapons complex has consolidated over the past decades, as well as some of the challenges of continued consolidation. We conclude by noting that all three of the examined areas (infrastructure, stockpile, critical skills) are inherently interdependent, as well as being strongly influenced by the overall DOE nuclear weapons budget. From fiscal years 2004-2010, a downward trend in the Weapons Activities budget resulted in a loss of purchasing power of 20 percent for NNSA's Defense Programs[22]; however, the current presidential administration has requested a nearly 10 percent increase in Weapons Activities funds[23] to enable the attainment of NNSA's future goals and to implement the requirements of the most recent Nuclear Posture Review[24].

Mathematical Tools for Quantifying the Effects of Weapons Enterprise Policies

There are four main categories of mathematical tools that our team has used to help NNSA quantify the effects of future stockpile decisions: simulation tools, optimization tools, economic analysis tools, and decision analysis tools. We cover each of these in turn, and the kinds of policy decisions each tool is best suited to help answer.

Simulation Tools

The goal of simulation tools is to mathematically represent the NNSA complex in a manner that captures the overall flow of operations, and then assess the impact of policy decisions by seeing how the system behavior changes. Our team has employed simulation tools in a number of different contexts, most notably including stockpile management and evolution of critical skills.

In terms of stockpile evolution, we have adopted a discrete event simulation approach, which offers added flexibility over a previously used systems dynamics approach[25]. In the greater industry, discrete event models have been used in the electronics[26], automotive[27], and

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[21] Ibid., 24-26.
[22] US Department of Energy, *FY 2012 Stockpile Stewardship and Management Plan*, 58.
[23] Ibid., 58.
[24] US Department of Defense, *Nuclear Posture Review Report* (Washington, DC: DoD, April 2010), http://www.defense.gov/npr/docs/2010%20Nuclear%20Posture%20Review%20Report.pdf. Goals for the complex are mentioned throughout the report, under the broad categories of: reducing the role of US nuclear weapons; maintaining deterrence at reduced nuclear force levels; and sustaining a safe, secure and effective nuclear arsenal.
[25] Arnie Heller. "Modeling the Future: a Computational Tool Aims to Help the US Create a Responsive Nuclear Enterprise," *Science and Technology Review* (December 2005), https://www.llnl.gov/str/December05/Shang.html.
[26] Robert Leachmann, Jeenyoung Kang, and Vincent Lin, "SLIM: Short Cycle Time and Low Inventory in Manufacturing at Samsung Electronics," *Interfaces* 32, no. 1 (Jan-Feb 2002), 61-77, http://interfaces.journal.informs.org/content/32/1/61.
[27] George Pfeil, Ron Holcomb, Charles Muir, and Shahram Taj, "Visteon's Sterling Plant Uses Simulation-Based Decision Support in Training, Operations, and Planning," *Interfaces* 30, no. 1 (Jan-Feb 2000), 115-133, http://interfaces.journal.informs.org/content/30/1/115.

health care[28] fields, among others, resulting in savings of up to billions of dollars. In our models, each of the sites in the NNSA enterprise is included, and operations affecting the state of the current stockpile (for instance, assembly and disassembly at the Pantex and Y-12 plants) are modeled in as great a degree of detail as possible (down to individual lines and parts, and their interrelations; see Figure 4). For micro-level policy decisions (affecting a single plant), we can infer the resulting effects on the entire system, and for macro-level policy decisions (affecting the entire stockpile at once), we can assess the impacts on each of the individual sites. Uncertainty can be readily incorporated in such models, including Monte Carlo analyses over different distributions of parameters.

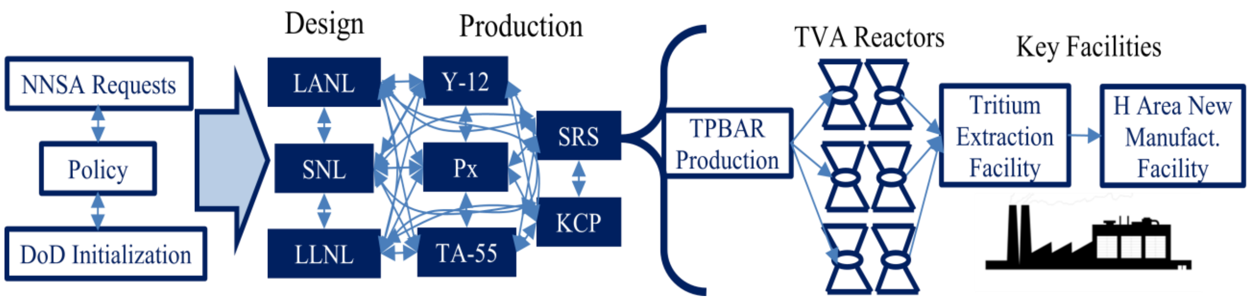

Figure 4. High-level schematic of our discrete event simulation model. Overall model structure is on the left, and some of the detail in the Savannah River site model is shown on the right.

For critical skills modeling, our team has applied tools to simulate the career progression of employees over time, including the acquisition and refinement of weapons-related expertise. We use the conceptual model in Figure 5, which is based on work in previous NNSA studies.[29]

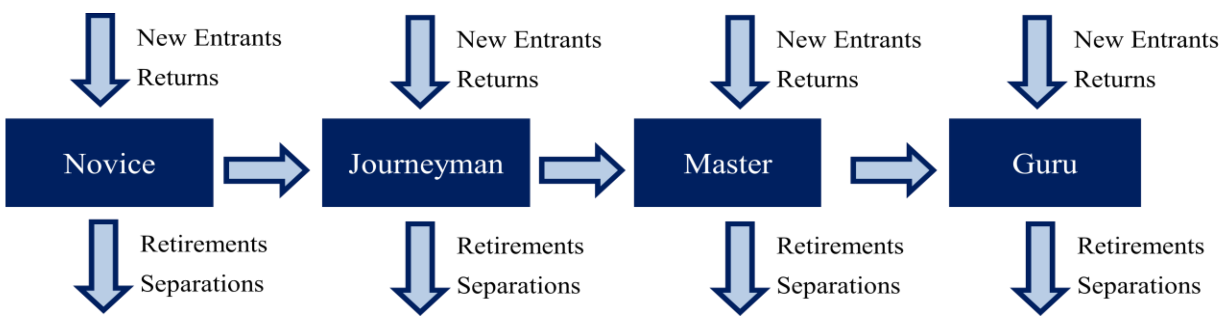

Figure 5. Conceptual model of critical skills evolution over the course of an employee's career.

In our model, transition rates are determined for all entries into and exits from the system, via historical hiring data, and data such as time to promotion are used to establish the transitions

[28] Kay Aaby, Jeffrey Herrman, Carol Jordan, Mark Treadwell, and Kathy Wood, "Montgomery County's Public Health Service Uses Operations Research to Plan Emergency Mass Dispensing and Vaccination Clinics," *Interfaces* 36, no. 6 (Nov-Dec 2006), 569-579, http://interfaces.journal.informs.org/content/36/6/569.

[29] US Department of Energy, *Right Size: Determining the Staff Necessary to Sustain Simulation and Computing Capabilities for National Security* (Washington, DC; NNSA ASC Office, October 2010), http://nnsa.energy.gov/sites/default/files/nnsa/inlinefiles/RightSize12-7-10SAND.pdf.

between levels[30]. Simulating the system over time reveals trends in the retention and attrition of different critical skills, which can help gauge the readiness status of the complex as a whole.

Optimization Tools

Often times it is desirable not only to predict how the complex might evolve over time, but to optimize the behavior of the complex under different scenarios. Optimization is in many ways a complementary approach to simulation (and the two approaches are often used together[31]): although simulation tools can typically model a system to a greater degree of detail, only mathematical optimization tools can provide solutions that are provably close to the best possible. The appropriate tool for the job depends on the question being asked and the required timeframe (optimization is particularly applicable for long-term policy questions; some companies will start with one approach and then switch[32]).

In a mathematical optimization framework, the parameters of the system in question are modeled as mathematical variables, and the behavior of the system is defined via a set of constraints over these variables. The quantities to optimize over are specified in terms of an objective function defined on the same variables. There are a variety of different tools available to solve such problems, according to the form of the objective function and constraints (such as linear, quadratic, or nonlinear)[33]. Such optimization approaches have previously been applied in the weapons complex, including production and dismantlement planning operations at Pantex[34] and prioritizing remediation techniques for hazardous waste cleanup across numerous DOE sites.[35]

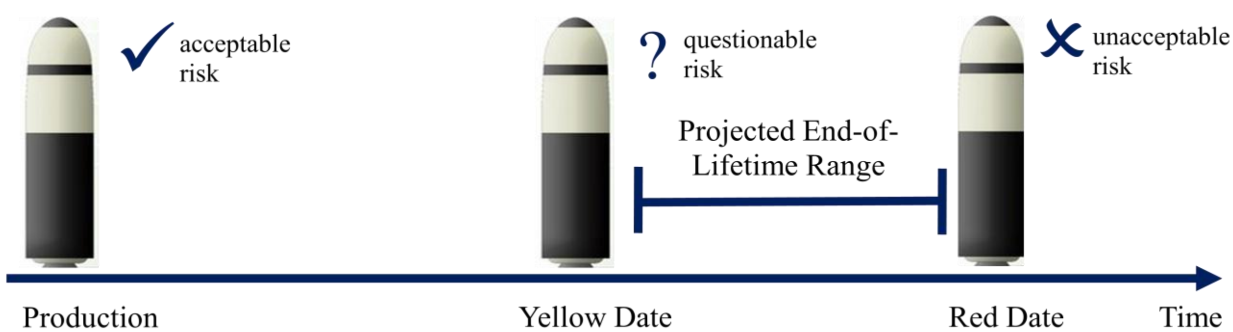

Figure 6. Definition of a weapon ‘red date’. A common model objective is to minimize the number of ‘red’ weapons per year.

[30] Foundational work in this methodology is described in John Edwards, “A Survey of Manpower Planning Models and their Application,” *Journal of the Operational Research Society* 34, no. 11 (Nov. 1983), 1031-1040.
[31] Ronald Toland, Jack Kloeber, Jr., and Jack Jackson, “A Comparative Analysis of Hazardous Waste Remediation Activities,” *Interfaces* 28 no. 5 (Sep-Oct 1998), 70-85, http://interfaces.journal.informs.org/content/28/5/70.
[32] Jeffrey Alden, Lawrence Burns, Theodore Costy, Richard Hutton, Craig Jackson, David Kim, Kevin Kohls, Jonathan Owen, Mark Turnquist, and David Vander Veen, “General Motors Increases its Production Throughput,” *Interfaces* 36, no. 1 (Jan-Feb 2006), 6-25, http://interface.highwire.org/content/36/1/6.
[33] See Operations Research/Management Science magazine’s annual optimization software review for a partial list: http://www.orms-today.org/surveys/LP/LP-survey.html.
[34] Edwin Kjeldgaard, Dean Jones, George List, Mark Turnquist, James Angelo, Richard Hopson, John Hudson, and Terry Holeman, “Swords into Plowshares: Nuclear Weapon Dismantlement, Evaluation, and Maintenance at Pantex,” *Interfaces* 30, no.1 (Jan-Feb 2000), 57-82, http://interfaces.journal.informs.org/content/30/1/57.
[35] Toland, Kloeber Jr., and Jackson, “A Comparative Analysis of Hazardous Waste Remediation Activities”.

Our team has developed a mixed-integer optimization model capable of calculating optimized NNSA sustainment and retirement paths to a desired stockpile size and composition, incorporating different infrastructure scenarios. This tool has been used to evaluate Nuclear Posture Review scenarios, the current NNSA program of record, and various proposed hybrid scenarios. The most common objective function we use is to minimize the total number of weapon red years (see Figure 6), in which a weapon is in the stockpile past its expected lifetime. This objective function ensures that the greatest possible fraction of the current stockpile is in good working condition and thus less likely to need additional attention or surveillance. Mathematically, the model is run in parallel (multi-threaded) on supercomputers, using a NNSA lab-developed algebraic modeling language[36].

Economic Analysis Tools

One of NNSA's chief tasks is to implement the recommendations of the Nuclear Posture Review within their allocated budget[37]. This budget includes different allocations for numerous stockpile, infrastructure, and science programs and campaigns[38]. We have developed economic models that project the cost trajectories of these programs and campaigns over the coming decades. In this context, stockpile costs include both sustainment and acquisition activities; infrastructure costs include sustainment, acquisition, and disposition/cleanup activities; and science costs include supporting the careers and development of weapons complex employees. Figure 7 shows an overall cost trajectory for NNSA along with an estimate of the uncertainty range within two standards of deviation, which was determined via Monte Carlo analysis. (This figure represents an aggregate view and our usual analyses include far more detail on the contribution of each of the constituent programs.)

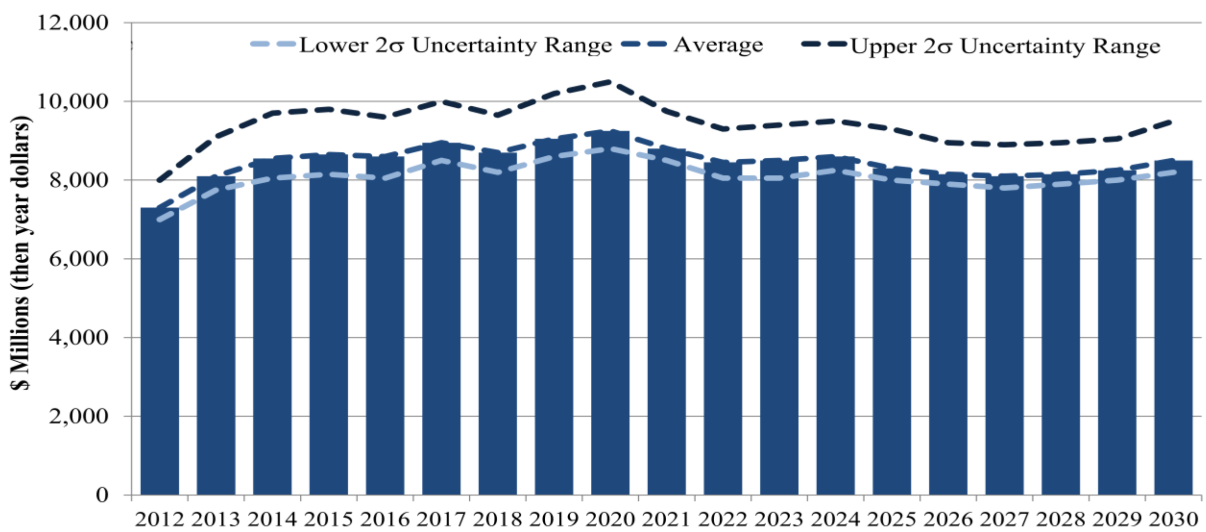

Figure 7. Overall cost projection for NNSA, with uncertainty bands for two standard deviations.

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[36] William Hart, Jean-Paul Watson, and David Woodruff, "Pyomo: Modeling and Solving Mathematical Programs in Python," *Mathematical Programming Computation* 3, no. 3 (Sep 2011), 219-260, http://www.springerlink.com/content/r061844312537 25q/.
[37] US Department of Energy, *FY 2012 Stockpile Stewardship and Management Plan*, 58.
[38] See US Department of Energy, *Department of Energy FY2012 Congressional Budget Request* (Washington, DC: DOE, February 2012), 62-68, http://www.cfo.doe.gov/budget/12budget/Content/FY2012Highlights.pdf.

In general, one of the biggest challenges in economic analyses is taking the outputs of numerous simulation and projection codes and stitching this together into an integral cost model. NNSA facility cost modeling alone encompasses numerous codes and has been the subject of entire workshops[39]. Care must be taken to include all relevant costs and also to avoid double-counting costs. Although we have limited our discussion to costs incurred by NNSA, Department of Defense costs and policies are strongly inter-related[40] (for instance, Secretary Gates has asked for $5 billion to be transferred from DoD to DOE to achieve Nuclear Posture Review objectives[41]). The issue of cost is likely to remain a key policy driver in future complex downsizing efforts.

Decision Analysis Tools

When addressing questions of policy, we often find that qualitative data (in particular, the preferences of different decision makers) are at least as important as quantitative data (raw numbers). Formalized in the 1960s[42], the field of decision analysis provides a rigorous framework in which such qualitative preferences can be encoded in a mathematically consistent and logically correct manner. This allows for a direct comparison of the relative value of different alternatives according to the stated preferences of decision makers. Such methods have been used to assess alternatives for the disposition of weapons-grade plutonium[43], the realignment and closure of army bases[44], and managing the nuclear waste from power plants[45], among others.

We use the techniques of multi-attribute utility theory[46], a form of decision analysis, to help quantify the enterprise consolidation preferences of decision makers. In such an analysis, different criteria of interest are represented as attributes, possibly with corresponding sub-attributes (see Figure 8 for an example we have used to quantify the relative goodness of different weapons in the stockpile). Each attribute (or sub-attribute) is associated with a value function, which can have a variety of forms; the relative values of different attributes are evaluated using mathematical trade-offs, which are elicited from decision makers. Decision-making alternatives are assessed via computing their scores on each of the value functions, then

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[39] For workshop contents, see Whitestone Research, "Whitestone Hosts the 2010 Facility Cost Planning Workshop for the Department of Energy Clients" (workshop, Napa, CA, May 25-26, 2010), http://www.whitestoneresearch.com/research/reports/facility-cost-planning-workshop.aspx.

[40] For a historical treatment of the costs of nuclear weapons, including both DoD and DOE estimated spending, see Stephen Schwartz, *Atomic Audit: The Costs and Consequences of US Nuclear Weapons Since 1940* (Washington, DC: The Brookings Institution, 1998).

[41] US Department of Defense, *Nuclear Posture Review Report*, i.

[42] Foundational work in this methodology is described in Ronald Howard, "The Foundations of Decision Analysis," *IEEE Transactions on System Science and Cybernetics* 4, no. 3 (Sep. 1968), 211-219.

[43] James Dyer, Thomas Edmunds, John Butler, and Jianmin Jia, "A Multiattribute Utility Analysis of Alternatives for the Disposition of Surplus Weapons-Grade Plutonium," *Operations Research* 46, no. 6 (Nov-Dec 1998), 749-762.

[44] Paul Ewing, Jr., William Tarantino, and Gregory Parnell, "Use of Decision Analysis in the Army Base Realignment and Closure (BRAC) 2005 Military Value Analysis," *Decision Analysis* 3, no. 1 (Mar 2006), 33-49, http://faculty.nps.edu/plewing/docs/Ewing-Tarantino-Parnell-deca%201060%200062.pdf.

[45] Ralph Keeney and Detlof von Winterfeldt, "Managing Nuclear Waste from Power Plants," *Risk Analysis* 14, no. 1 (Feb 1994), 107-130.

[46] This framework is fully described in Ralph Keeney and Howard Raiffa, *Decisions with Multiple Objectives: Preferences and Value Traedeoffs* (New York: Wiley, 1976).

combined using the elicited trade-off values to calculate a single numerical utility that can be compared across different alternatives.

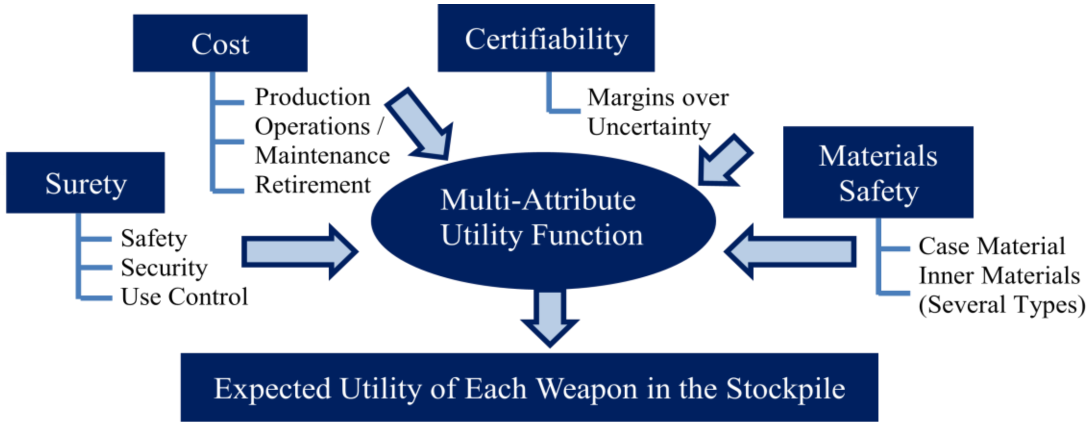

Figure 8. Components of a tool for computing the overall utility of each weapon in the stockpile.

Conclusion

In this paper we have observed how mathematical tools have been used to help NNSA in making policy decisions relating to weapons complex consolidation, a process that is ongoing. Until this point we have not mentioned a crucial part in this process, which is the availability of real quantitative data that can be used in such models. We have been fortunate to work with excellent people from around the NNSA complex who have provided us with such data, as well as site-specific expertise that is crucial to maintaining the accuracy of our models. Just as policy cannot be made in a vacuum, mathematical models cannot be truly useful without data. This cooperation and trust between sites in the NNSA complex is instrumental to the progress that we have made and continue to make in informing policy, and we hope to continue building and refining such models together for years to come.[47]

[47] Although I am the sole author on this paper, the models I have described are very much a group effort. I am especially indebted to Clifford Shang for his excellent guidance in leading our team. Our group at Lawrence Livermore also includes Victor Castillo, Lisa Clowdus, John Compton, John Estill, John Futterman, William Liou, Katy Lu, Bernard Mattimore, Peter Norquist, Marilyn Pickens, Tri Tran, William Romine, and Jeene Villanueva; I am grateful to them all for many excellent discussions. Special thanks are due to NNSA for the intellectual and practical support of members of its management staff: Tim Driscoll, John Evans, Alan Felser, Robert Herrera, Michael Thompson, Jeff Underwood, and Kyle Wagner. We have also benefitted greatly from interactions with and support from our colleagues at the Department of Defense: Lou Arnold, Pat McKenna, Mark Wittig (STRATCOM), Andrew Wiedlea (DTRA), and Rick Paulsen (AFNWC).